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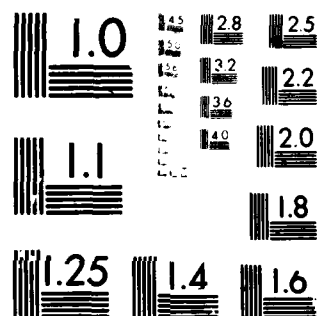
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Report No. FAA-RD-79-106



FEASIBILITY OF OFFSET CARRIER SYSTEMS FOR AIR TRAFFIC CONTROL

AMAF Industries, Inc.
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October 1979

Second Interim Report

Document is available to the U.S. public through
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Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

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Technical Report Documentation Page

| | | | |
|---|---|--|--|
| 1. Report No. 18 FAA-RD-79-106 | 2. Government Accession No. AD-A084 044 | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle Feasibility of Offset Carrier Systems for Air Traffic Control | | 5. Report Date October 1979 | 6. Performing Organization Code 5171 |
| 7. Author(s) J. David Claiborne | | 8. Performing Organization Report No. | |
| 9. Performing Organization Name and Address AMAF Industries, Inc. P.O. Box 1100 Columbia, Maryland 21044 | | 10. Work Unit No. (TRAIS) | |
| 12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, DC 20590 | | 11. Contractor or Grant No. DOT-FAA/8WAI-830 | |
| | | 13. Type of Report and Period Covered Second Interim Report . 11. 2 September 1979 for period ending Sep 79 | |
| 14. Sponsoring Agency Code FAA/ARD-200 | | | |
| 15. Supplementary Notes | | | |
| 16. Abstract <p>A brief description of FAA trials of offset carriers systems and multiple outlet systems is given. Short descriptions are also given of existing offset carrier systems in Great Britain and the ARINC system in the United States. The communication deficiencies that could be remedied by an offset carrier system are listed. A short discussion is given concerning the system design deficiencies inherent with an offset carrier system. No conclusions are made concerning the usefulness or practicality of an offset carrier system.</p> | | | |
| 17. Key Words Offset Carrier Multicarrier delay difference distortion | | 18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161. | |
| 19. Security Classif. (of this report) Unclassified | 20. Security Classif. (of this page) Unclassified | 21. No. of Pages 16 | 22. Price |

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|----------------------------|------------------------|----------------------------|---------------------|-----------------|
| LENGTH | | | | |
| in | inches | 2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| AREA | | | | |
| in ² | square inches | 6.5 | square centimeters | cm ² |
| ft ² | square feet | 0.09 | square meters | m ² |
| yd ² | square yards | 0.8 | square meters | m ² |
| mi ² | square miles | 2.6 | square kilometers | km ² |
| | acres | 0.4 | hectares | ha |
| MASS (weight) | | | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| VOLUME | | | | |
| teaspoon | teaspoons | 5 | milliliters | ml |
| Tablespoon | tablespoons | 15 | milliliters | ml |
| fluid ounce | fluid ounces | 30 | milliliters | ml |
| c | Cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| ft ³ | cubic feet | 0.03 | cubic meters | m ³ |
| yd ³ | cubic yards | 0.76 | cubic meters | m ³ |
| TEMPERATURE (exact) | | | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exact). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Pt. 2, \$2.25, SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|----------------------|-----------------------------------|-------------|---------------|-----------------|
| LENGTH | | | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| km | kilometers | 1.1 | yards | yd |
| | | 0.6 | miles | mi |
| AREA | | | | |
| cm ² | square centimeters | 0.16 | square inches | in ² |
| m ² | square meters | 1.2 | square yards | yd ² |
| km ² | square kilometers | 0.4 | square miles | mi ² |
| ha | hectares (10,000 m ²) | 2.5 | acres | |
| MASS (weight) | | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| VOLUME | | | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| m ³ | cubic meters | 36 | cubic feet | ft ³ |
| m ³ | cubic meters | 1.3 | cubic yards | yd ³ |

TEMPERATURE (exact)

| | | | | |
|--|---------------------|-------------------|------------------------|----|
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |
| <p>A vertical temperature conversion scale. On the left, the Celsius scale is marked from -40 to 200 in increments of 20. On the right, the Fahrenheit scale is marked from -40 to 200 in increments of 20. A horizontal line runs across the middle of the scale, with the conversion formula '9/5 (then add 32)' written above it. The scales are aligned such that 0°C corresponds to 32°F, 100°C to 212°F, and -40°C to -40°F.</p> | | | | |

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1.0 INTRODUCTION

1.1 BACKGROUND

The Federal Aviation Administration (FAA) is looking for a means of improving the quality of its multiple outlet radio systems for air/ground communication. In particular, the FAA is interested in the possibility of using an offset carrier system (OCS). In order to gain more information on OCS and multiple outlet systems, an investigation is being conducted.

The first phase of the investigation examined the principles of offset carrier theory and practice. A brief history of the evolution of offset carrier systems was developed, tracing the origins from a British police radio system in the late 1940s to the present day systems in Great Britain and the United States. The applicability of an OCS to FAA air/ground communications was also investigated in the context of four existing air traffic control (ATC) sectors which could possibly benefit from a multiple outlet system. This work was documented in an interim report. 1/

Information on FAA and other trials of offset carrier systems and other multiple outlet systems approaches was to be examined in Phase 2. This information was to be assimilated, reviewed, and correlated, paying particular attention to the following areas:

- a. Communication deficiencies based on existing needs and initial requirements.
- b. Identification of system design deficiencies in order to determine airborne or ground subsystem characteristics not compatible with a multiple outlet system.
- c. Characteristics that are common to all multiple outlet systems.

The work on this phase is documented in this second interim report.

The third phase of the investigation will consist of the preparation of an engineering analysis of major problems, both existing and potential, in the implementation and use of an offset carrier system. This work will be documented in a final report, incorporating applicable information from the previous interim reports.

1/ AMAF Industries, Inc., Feasibility of Offset Carrier Systems for Air Traffic Control, First Interim Report, September 1979. FAA-RD-79-95

1.2 SCOPE

The investigation is subject to several limitations. Those particularly pertinent to this report are:

- a. The effort is limited to very high frequency (vhf) communications.
- b. Applicable standards or performance criteria shall be obtained from the Federal Register, U.S. National Aviation Standard for the VHF Air-Ground Communication System, and FAA handbooks.
- c. Minimum analysis shall be applied to operational impact of such factors as aircraft density, channel loading, communications workload, and probabilities of interference other than between offset system user elements.
- d. Determination of feasibility is not to be the product of the effort.

Keeping within these guidelines, this report addresses the three areas listed previously; communications deficiencies, system design deficiencies, and common characteristics; while looking at FAA and other trials of offset carrier systems and other multiple outlet systems. Unfortunately, much of the testing performed within the FAA on offset carrier systems has not been formally documented. Therefore, information has been obtained through meetings and conversations with cognizant FAA personnel. While this form of information gathering provides qualitative information, little quantitative information is gained on which further analysis could be done.

1.3 APPROACH

The body of this report is divided into three sections. The first section gives a brief description of FAA trials of offset carrier systems and multiple outlet systems that have been performed in the past. Short descriptions are also given of existing offset carrier systems in Great Britain and the ARINC system in the United States. The second section explains the communications deficiencies that possibly can be corrected by an offset carrier system and gives the reasons that the deficiencies exist. The final section explains the system design deficiencies that have appeared in multiple outlet systems. This section is confined to the characteristics of problem areas peculiar to multiple outlet systems that are traceable to a design deficiency.

2.0 MULTIPLE OUTLET SYSTEMS

2.1 FAA SYSTEMS

The FAA has conducted trials of offset carrier systems in the Western Region, the Great Lakes Region, and the Southwest Region. The Alaska Region has used an offset carrier system for the past several years on a regular basis. Multiple outlet systems employing selective keying are also being used in some regions. Information on experiences within the FAA are summarized below.

2.1.1 WESTERN REGION

In the late sixties, the Western Region experienced a communication heterodyne in aircraft simultaneously receiving transmissions from two different flight service stations (FSSs) operating on the same frequency. To move the heterodyne out of the audio band of the airborne receiver, an offset in the transmitter frequencies of +6 kHz and -6 kHz was tried with no change in the coverage from each FSS.

The trial differs from other offset trials in that the ground outlets were independent of each other and transmitting different messages to separate sectors. The offset frequencies relieved the disturbing effects of the heterodyne, but the pilots continued to hear two conversations when in the region of overlapping coverage. It was concluded that the pilot could tolerate the interference from the second conversation, but an audible heterodyne prevented useful communication.

An experimental external oscillator, connected to the TV-36 transmitters in order to provide improved stability, proved to be unstable and unreliable, forcing an early end to the trial. No additional operational burden was placed on the controller or the pilot by the use of the offset carriers. When the offset carrier system was operating properly, there were only minor complaints about the operation from either the controllers or the pilots.

2.1.2 GREAT LAKES REGION

The Great Lakes Region conducted a trial of an offset carrier technique, however, details of the trial were not available in time for this report.

2.1.3 SOUTHWEST REGION

In the Southwest Region, several of the low altitude control sectors are of such large size (length and width) that the controllers and pilots do not have direct, continuous air-ground communications. Because of the limited availability of additional frequencies, and of the desire to provide both the controller and the pilot with "hands off" communication throughout the sector on a single frequency, trials were conducted using offset carriers. Trials at four locations were conducted in 1978 and 1979. Earlier trials were performed in 1971 and 1972.

The use of the offset permitted the controller to key all transmitters in his sector simultaneously. There were reports of holes in the coverage that appeared to stem from cancellation of signals due to phase differences between signals from adjacent site transmitters. On the whole, the controllers found the performance of the offset system unacceptable due to poor reception by aircraft and to echo-like distortion. The manual method of selectivity keying the appropriate transmitter was resumed after the trial.

The principal source of complaints from pilots were heterodynes and weak signal or no signal in certain areas. The complaints seemed to be more from the general aviation than from air carriers. No definite causes were established for the heterodynes or signal fading.

2.1.4 ALASKA REGION

The Alaska Region has used offset carrier for several years on a regular basis. The systems were implemented because of the requirement for common frequencies at two or more air/ground outlets in the same air traffic control sector. The use of offset carriers relieved both controllers and pilots from switching frequencies as an aircraft progressed along a route in a sector. Also, the use of simultaneous broadcasts at all outlets in a sector provided information to all aircraft in an area as to the movement of nearby aircraft. The offset carriers were used to some extent in each sector of the Anchorage ARTCC as required for high/low altitude coverage.

The controllers like the simplicity, organization, and safety of having sector aircraft on the same assigned frequency. The echoes, double talk, and heterodynes delayed (and on occasion prevented) effective communications. Operation of the offset system was like conventional single outlet operation. The pilots, too, operated their radios as in a conventional air/ground communication system. No definite sources were identified as the causes of reported echos/double talk and heterodyne interference.

With the advent of airborne communications equipment configured for 25 kHz channels, the transmitter offset plus drift often fell on the skirt of the selectivity curve of the receiver. The resulting conversations could not be understood by the pilot. Presently, the offset system is being phased out in Alaska.

2.1.5 ROCKY MOUNTAIN REGION

The Rocky Mountain Region has not conducted any trials of offset carrier systems. They do, however, use multiple outlets, selectively keyed, using a common frequency to provide coverage over the entire sector. The size and the topography of the sector make coverage from a single RCAG nearly impossible.

The use of multiple outlets on a common frequency requires the controller to selectively key a specific transmitter based on his knowledge of the aircraft's location within the sector. Since only one transmitter is keyed, there is no problem of heterodyne in the airborne receiver. However, the single

keying also limits the percentage of the sector in which the conversation can be heard. Aircraft in other parts of the sector may not hear the conversation.

Receivers are colocated with transmitters. Ordinarily, the audio from receivers in a sector combine to produce one output at the controller's position. The controller, however, has the option of using an audio comparator located at the ARTCC that automatically selects the strongest signal and passes only that signal to the controller. The use of the comparator is kept to a minimum because of the concern about missing contact, and is generally switched into the received channel when echo-like distortion renders the signal unintelligible. While the comparator has the ability to make a bad situation better, the consistency of its performance is not at the level desired for equipment in the air/ground communications system.

2.2 THE CLIMAX SYSTEM OF GREAT BRITAIN

The National Air Traffic Services (NATS), the FAA's British counterpart, installed its first offset carrier network in 1947. Since then, the system has been expanded and improved in order to cope with the greater volume of air traffic and the continuing reduction in rf channel spacing. The current system operates in a 25 kHz channel environment with a ± 7.5 kHz and a zero offset carrier system. This places a possible 7.5 kHz beat note in the receiver. Plans call for making the offsets ± 7.5 kHz and ± 2.5 kHz when aircraft receivers are modified so that 5 kHz beat notes will be rejected from the audio output. The transmitter stability is maintained within 0.00003%, making the resulting maximum frequency drift about 40 Hz. Transmitter and receiver sites are all physically separated by at least 2.5 miles. Typically, four transmitters or four receivers are connected to each antenna, in order to keep down antenna and masts costs.

Since it began operating in the 25 kHz environment in January 1974, no complaints have been received from any source which would imply fundamental deficiencies in the design of the system. The combination of multiple signals in the aircraft receiver has not proved to be a significant problem, although a few complaints have arisen. The problems were thought to be unique to the location and the aircraft involved, and no complaints have been received since the initial investigation and corrections.

The British use an automatic rf voting scheme for the choice of receiver available to the controller at all times. This is done to optimize signal quality and to eliminate any potential phasing effects which could otherwise occur in the air/ground transmission path due to differential time delays in the propagation paths. This switching is done by a multi-carrier remote control and monitoring system installed at all remote sites, which selects, on the basis of a coded representation of individually received carrier amplitudes, the "best" signal and switches out the unwanted (inferior) legs of the area coverage system at the control center. 2/

2/ Hayes, D.W., unpublished paper, UK VHF Area Communication System, Civil Aviation Authority, National Air Traffic Services, Telecommunications Division, London, August 1979.

2.3 THE ARINC SYSTEM

ARINC operates a radio network for the air carriers to conduct their operational communications. The network consists of several chains of remote radio sites located along the major air routes. Each route is assigned a single frequency, but operates the individual sites with offset frequencies of +8 kHz, +4 kHz, and zero. The sites are typically three hundred miles apart. The sites along the chain are linked to a single control site via phone lines.

The ARINC networks utilize specially designed exciters that maintain transmitter stability at 0.00005% over very long periods. The transmitted audio is sharply low pass filtered at about 2500 Hz, while the aircraft receivers are specified to reject frequencies above 3740 Hz, in accordance with ARINC Characteristic 716. ^{3/} This essentially eliminates heterodyne problems caused by the mixing of two adjacent carriers. The heterodyne problem is further relieved by arranging the stations on the chain so that immediately adjacent stations are at least 8 kHz apart in frequency when ever possible.

ARINC has not had significant problems with the offset carrier network. For the most part, service has been very satisfactory. There have been problems related to the squelch circuitry in aircraft receivers and connected with audio distortion due to echo effects at the ground receivers. The squelch circuit problem has been attributed to the radio receiver design and not to the offset carrier network design. The audio distortion is not considered a major problem, and it should be totally eliminated when ARINC installs a computer controlled voting scheme that will select both receiver and transmitter.

^{3/} ARINC, Characteristic 716, Airborne VHF Communications Transceiver,
Aeronautical Radio, Inc., Annapolis, MD, March 1, 1979

3.0 COMMUNICATIONS DEFICIENCIES

It is well known that in some air traffic control sectors the limitations of radio line of sight, large distances between sector boundaries, terrain conditions, or limits in conventional system performance create the need for multiple radio outlets. In present configurations of multiple sites, manually selected keying is necessary to prevent heterodynes or other interferences in ground-to-air communications. In air-to-ground communications, the ground receiver coverage overlap areas present situations wherein the combined audio from more than one remote receiver may produce "barrel effect", excessive distortion or mutual interference in the form of fading or noise.

Communication deficiencies in FAA offset carrier trials or multiple outlet systems derive from one or more of three basic sources. These are the audio subsystem, the rf subsystem, and the system user aspects.

Deficiency in the ground audio subsystem evolves primarily from audio phase changes or inversions causing distortion, drop-out, or "barrel effect". This condition pertains to both the single frequency multiple outlet system as well as the offset carrier system that use conventional audio combining techniques.

A communication deficiency in the airborne audio subsystem was noted in some instances wherein an otherwise appropriate difference frequency (offset) creates a beat note (heterodyne) that passes through a wideband audio channel to override or interfere with voice communications. Insufficient ground transmitter stability also contributes to this problem.

Deficiency is noted in the rf subsystem of both the ground and the airborne terminals. The ground terminal omnidirectional rf patterns overlap in specific areas established by a complex combination of altitude, terrain influence or reflections, audio phase variations in carrier modulations, and possibly from aircraft antenna pattern perturbations. Therefore, areas of holes and weak signals develop in the aircraft and ground reception. The location of these areas has been known to shift to a new geographical location in offset system tests when the phase of audio at one of the ground terminals was reversed.

Deficiency in communications with regard to the user of a single frequency multiple outlet system is most notable in that a controller is required to select a transmitter and a pilot may not be aware of an ongoing communication. Having to selectively key a transmitter places an additional burden on the controller, since he must also monitor or assume an aircraft location relative to his transmitters. In some sectors, the controller may have as many as five transmitters to select. When a selected transmitter is keyed, only the aircraft within the area of coverage of that transmitter can hear the conversation. A portion of the sector is not covered. Consequently, a pilot may inadvertently disrupt a communication, or he may not hear information of importance to him.

A somewhat different problem occurs with flight service stations (FSS's). Communication with FSS's involves a limited number of frequencies that are reused over the entire National Airspace System (NAS). Consequently, there are areas where the same frequency can be received by an aircraft from two different ground sites. This produces a heterodyne in the receiver and disrupts communication.

Generally, the cost of implementation of offset system trials was not a major or restrictive factor since the costs were nominal. All trials used existing RCAG's and FSS's. The only equipment modification connected with the offset carrier system trials was the use of external oscillators for an FSS trial or crystal changes in RCAG transmitters. Additional maintenance was not required during the RCAG trials. While the offset trials required minimal cost and support, the results were inconclusive.

4.0 SYSTEM DESIGN DEFICIENCIES

Examination of the offset carrier trials and systems yields four main design deficiencies. They are:

- a. Audio distortion appearing at the controller's position due to combining the outputs of multiple receivers.
- b. Transmitter stability in ground transmitters.
- c. Aircraft receiver IF and audio bandwidths.
- d. Squelch control in the aircraft.

The final three deficiencies are more in the area of equipment design than in the actual area of the system design.

4.1 GROUND AUDIO DISTORTION

The ground audio distortion results from aircraft transmissions being received by more than one ground receiver. There is some difference in arrival time at the receivers due to propagation path differences. The delay difference may be further compounded when the signals travel over the phone lines to the ARTCC. Also, differential Doppler causes frequency shifts between the multiple receive sites. At the ARTCC, the various signals are added together to produce a single audio output. The result is often distorted, yielding an audio signal that is reported to sound like the speaker has his head in a barrel. It is also possible to have a phase difference which exactly cancels the audio signal at a specific frequency.

The echo distortion, or barrel effect, is the most prevalent controller complaint in the FAA trials. The primary source of the phase delays encountered during the trials has not been determined. A report on the problem at Seattle ARTCC associates the barrel effect with increased solar flare activity and area weather conditions which created inversions conducive to above normal transmission ranges for vhf communication. 4/ There is, however, no information on aircraft location relative to the RCAG site when the barrel effect occurs.

The undesirability of the distortion resulting from the combination of two or more signals shifted in phase is due to an unpleasant audio sound and loss of intelligibility. Qualitative assessment of the problem is difficult. A British experiment found that intelligibility was improved when a delay of 5-10 milliseconds was deliberately introduced. 5/ Unverified information has indicated that the Air Force has had good results with a split headset technique where each ear receives audio from a different receiver. Neither of these techniques is believed to be practical for FAA use.

4/ FAA, Test Installation of an Audio Amplitude Selector Unit, Internal Memorandum, 7 July 1972.

5/ Raven, P.F., A Method of Improving Reception with VHF Mobile Radio Telephones Using Multiple Transmitters and Audio Delay, IERE VII, London, 1978, pp 19-28.

The primary means of combating the barrel effect has been to use a comparator or voting network. This device selects the "best" signal for passing to the control position and excludes the inferior ones. The devices differ as to how the "best" signal is determined. The units used by the FAA are installed at the ARTCC and vote on the highest audio signal level. While the device has provided satisfactory service at the Seattle ARTCC and ARTCCs within the Rocky Mountain Region, it does have problems. There are times when the loudest signal is the one that is the noisiest, rather than the most intelligible. There have also been cases of undesirable switching between good and bad signals due to speech pauses by the speaker. These problems are essentially eliminated if the voting is based on the received rf signal. This requires a monitoring device at the RCAG and a means of relaying the rf signal level to the voting device at the ARTCC. Once these difficulties are overcome, this type of device functions well, as is evident from reports on the British system.

A disadvantage of known voting devices is that, during air/ground transmissions, all receivers are muted except one. This enhances the possibility of missing a weak call from the area of receiver B while a strong signal is coming from receiver A. At present the Rocky Mountain Region avoids this problem somewhat by using its comparators only when necessary. At all other times, all receivers are combined to form the controller's audio. The number and impact of missed calls resulting from a comparator operating continuously, as in Britain's control centers, is unknown.

4.2 TRANSMITTER STABILITY

One fundamental requirement of an offset carrier network is that the transmitters be stable enough to prevent them from drifting to the point where the heterodyne of two carriers could show up in the audio signal received on the aircraft. The current transmitters being used by the FAA in the RCAG, the ITT AN/GRT-21, has a specified frequency stability of $\pm 0.001\%$, although field checks indicate it is better. The ARINC network and the Climax network use transmitters with frequency stabilities of $\pm 0.00005\%$ and $\pm 0.00003\%$ respectively.

4.3 AIRCRAFT AUDIO DISTORTION

Audio distortion in the aircraft arises from three sources. One is the addition of two identical signals that are offset in carrier frequency and have a phase difference due to different propagation paths. The only report found of this problem was in the British Climax system where one transmitter was on land and the other transmitter was offshore. The problem was remedied by placing some delay circuitry in the control center between the controller and the appropriate phone lines.

The second source of audio distortion is the heterodyne signal arising from two carriers offset in frequency. Ideally, the carriers are offset to an extent that the tone produced by their mixing is out of the audio bandwidth of the aircraft receiver. This is not always the case. The applicable FAA regulation, Order 6510.6 which is the standard for all aircraft participating in the Common Civil/Military Air Traffic Control System, calls for an audio passband between 300 Hz and 2500 Hz that does not vary more than 3 dB

over the entire range. Outside the band, however, the response is only required to fall continuously. If the rolloff is not steep enough, the heterodyne tone can be present in the audio output. ^{6/} The problem is more prevalent in general aviation aircraft because air carrier's radios must also conform to ARINC Characteristic 716. This requirement states that frequencies above 3750 Hz must be attenuated at least 20 dB and preferably 40 dB in air carrier receivers. This is a definite requirement for use of ARINC's OCS which has 4 kHz spacing between offset frequencies.

The third potential source of audio distortion is the response characteristic of the IF passband in the radio receiver. This passband is often designed to receive a single frequency, within the tolerances of the transmitter and receiver oscillators. If the passband is not wide enough or falls off too sharply, signals on carriers that have significant offsets could be adversely distorted. This problem is not severe as the first two since most aircraft receivers do have IF passbands compatible with OCS.

4.4 RECEIVER SQUELCH CONTROL

In the past, aircraft radio manufacturers have been encouraged to develop squelch circuitry that can distinguish between communication signals and the usual type of interference and receiver background noise which obscure such signals. Sophisticated squelch systems have been developed which automatically adjust the squelch threshold to match the masking level of the noise so that the user can take full advantage of the highest possible sensitivity capability in the receiver when the aircraft is away from ground generated noise conditions. Conversely, the squelch threshold will be automatically raised in the presence of heavier noise levels near industrial areas.

The problem arises because these types of squelch controls perceive a second signal, offset at a different frequency, as unwanted noise components and thus mute the receiver audio, even though both signals are desired signals. Both ARINC and the British have experienced this problem in their offset carrier systems. The only solution at present is to have the aircraft radio operator override or otherwise desensitize his squelch control.

^{6/} FAA Order 6510.6, U.S. National Aviation Standard for the VHF Air-Ground Communications System, Department of Transportation, November 11, 1977.

5.0 CONCLUSION

This report is an interim report prepared to document the second phase of a three phase investigation. The purpose of the second phase was to gather information on OCS and identify problems that exist. No conclusions are made at this stage of the investigation, because this type of work will be done in the third and final phase. Conclusions pertinent to the feasibility of OCS and how the various system design deficiencies could be corrected will be documented in the final report.